FINAL TECHNICAL REPORT
1 April 1998 - 31 March 2001

Antiprotons, Antihydrogen and Mass Spectroscopy

Principal Investigator: Gerald Gabrielse, Harvard University, Cambridge, MA 02138

Grant Number: F49620-98-1-0379

1. **Objectives: List the objectives of the research effort or the statement of work: This may be omitted if there has been no change. State new or revised objectives if they have changed and the reason why.**

For some time, in and outside of the Air Force, there has been speculation about possible uses for confined antimatter. In the Star Trek television series, confined antimatter propelled the Enterprise. Speculations about the possible confinement of antimatter and about the uses of confined antimatter have been carried out by people with a dangerously wide range of expertise. Some have simply watched too much Star Trek, while others have carried out a more informed and thoughtful analysis.

A major problem has always been an almost complete lack of hard experimental information and experience with antimatter confinement. The reason is that antiprotons are in extremely short supply. Right now, the only place where low energy antiprotons are available is the CERN Laboratory in Geneva, Switzerland. Obtaining antiprotons from this unique facility requires a scientific goal and a recognized experimental expertise, especially for Americans insofar as our government does not support the European CERN Laboratory. Access to antiprotons is awarded competitively and there are many more European groups requesting access to antiprotons than can possibly be accommodated.

Our first scientific goal is comparing the masses of the antiproton and proton, to make the most stringest test of CPT invariance with the baryon system. By four orders of magnitude, our new measurement just completed is the most precise of CPT invariance made with baryons, with C, P and T represented the charged conjugation, parity, and time reversal transformations. The invariance of physcial laws under CPT transformations is widely assumed to be true, despite the possibility to violate P, CP and T separately, because it is not possible to construct a Lorentzian variant local field theory which is not invariant under CPT. A second ambitious goal for this research program is to produce and study antihydrogen atoms for the first time. A greatly improved comparison and CPT test should be possible with cold, stored antihydrogen and hydrogen. More details are given in the Statement of Work and in the body of the proposal.

Our scientific goals required and allowed us to develop many antimatter cooling and confinement techniques. The number of antiprotons cooled and captured in these initial experiments has been modest as one would expect for initial studies on a new frontier. However steady progress has been made and continues. We now know that heavy antimatter particles can be slowed and cooled tremendously, reducing their energy by a factor of 10,000,000,000. We now know that antiprotons can be confined and stored for months at a time. Although much more will be said about the new techniques and demonstrations arising from this antiproton

research program, the point here is that a base of demonstrated techniques related to confinement of antimatter has been established and is growing. The slowing, cooling, and confinement which we now do routinely was considered by some to be outlandish and impossible at the outset of this antiproton research project.

The base of understanding, expertise, and techniques related to antimatter confinement and use has been the payoff to the Air Force so far. In the future, the expectation is that this base will expand to include larger and larger numbers of confined antiprotons and the production of the first antimatter atoms, antihydrogen. The scientific motivations for continued antiproton study are strong and are admired at the CERN Laboratory, as are the experimental accomplishments we have made while supported by AFOSR. This will insure our unique access to antiprotons at CERN as long as CERN elects to continue antiproton production.

Other advances pioneered in this research program are already beginning to impact nuclear magnetic resonance (NMR), ion cyclotron resonance (ICR) and magnetic resonance imaging (MRI). A Penning trap which provides a large access to the interior of the trap, unlike the traditional hyperbolic electrodes used for precision experiments, allows even a single elementary particle to be isolated and detected. As a result, a growing number of chemists and physicists doing ICR spectroscopy are therefore utilizing the new designs for compensated traps which are continually being developed and refined as part of this research program. A ``self-shielding" superconducting solenoid system which cancels fluctuations in the ambient magnetic field was also developed. This is patented, and is now being marketed by at least 3 magnet companies. Such systems are being purchased for ICR mass spectroscopy and NMR, and the design of MRI imaging systems have been adjusted to provide some improvement. Nine companies bid on a US small business initiative contract to allow companies to further implement this technology.

2. **Status of effort: A brief statement of progress towards achieving the research objectives.**

Over the last ten years, with AFOSR support, our small team invented and developed the techniques that allow accumulating cold antiprotons at 4 Kelvin. This is an energy that is 10^{10} times lower than the lowest energy at which antiprotons were previously available. In widely reported and appreciated steps, we used these antiprotons to improve the comparison of antiproton and proton charge-to-mass ratios by a factor of 10^5. Along the way, we have spun off a patent and several techniques used in NMR, MRI and ICR. Both our ATRAP Collaboration and the competing ATHENA Collaboration will use our techniques for slowing, trapping and cooling antiprotons. The new Antiproton Decelerator (AD) facility, and the continuation of antiproton physics at CERN, derives from our demonstration that we could accumulate antiprotons in a small trap for much less cost than it took CERN to accumulate them in a large storage ring.

The new facility makes it possible for us to focus directly upon the production and study of cold antihydrogen. There has been much recent progress. First is an important experimental advance. For the first time, we were able to confine cold antiprotons and cold positrons together and make them interact -- bringing us much closer to cold antihydrogen than anyone has ever been before.

Second, CERN has given final approval to our ATRAP Collaboration. Third, a promising theoretical framework for quantitative comparisons of CPT tests has just appeared.

Precise laser spectroscopy of antihydrogen and hydrogen offers a much better test of CPT invariance with leptons and baryons than has previously been possible. There is no more fundamental pillar of modern physics than our assumption that reality is invariant under CPT transformations. Nonetheless, there are so few precise experimental tests of CPT invariance that we easily summarize all three -- one with mesons, and one each of lesser accuracy with leptons and baryons. As physicists, we were wrong in the past to assume *P* invariance, and we were wrong again to assume *CP* invariance. Now we have a unique opportunity to test at a much greater sensitivity with leptons and baryons, whether *C,P* and *T* together provide a fundamental invariance that is not provided by either *C, P* or *T* alone or in pairs.

The ATRAP Collaboration is a uniquely qualified team. Beside the accomplishments mentioned above, we have pioneered the precise spectroscopy of hydrogen, invented laser cooling, first slowed and trapped atoms, and first cooled and performed laser spectroscopy on trapped hydrogen. On the way to the precise spectroscopy of antihydrogen we have the following steps.

1. Accumulating 10^7 antiprotons at 4 K from one hour of AD antiproton pulses.
2. Accumulating 4 K positrons at a density of $10^8/cm^3$ and higher during the same period.
3. Cooling antiprotons with positrons in a nested trap.
4. Observing and optimizing the formation of cold antihydrogen using the imaging annihilation detector.
5. Enhancing the formation rate by the appropriate tuning of a laser, via stimulated radiative recombination either directly from the continuum or following an initial three-body recombination.
6. Trapping of cold antihydrogen in a magnetic trap.
7. One photon spectroscopy of antihydrogen $1s$ - $2p$ with a continuous Lyman alpha source.
8. Near resonant 2-photon spectroscopy of $1s$ - $3s$ and $1s$ - $3d$.
9. Off resonant 2-photon spectroscopy of antihydrogen $1s$ - $2s$.

This is an ambitious program, and in implementing these steps sequentially will, of course, require many parallel apparatus developments and tests. Nonetheless, the scale and size of the experimental apparatus is still what is appropriate for a university laboratory.

The case is exceedingly strong for using laser spectroscopy of antihydrogen to improve by orders of magnitude upon CPT tests done with leptons and baryons. Deep and determined probing of such fundamental assumptions is one of the great traditions in physics. In addition, this particular line of research has already generated new techniques, inventions and applications. We have a well-organized team of proven groups whose successes have made antihydrogen studies possible. We have a well thought out strategy and are already hard at work.

3. **Accomplishments/New Findings: Describe research highlights, their significance to the field, their relationship to the original goals, their relevance to the AF's mission, and their potential applications to AF and civilian technology challenges.**

4. **Personnel Supported: List professional personnel (Faculty, Post-Docs, Graduate Students, etc.) supported by and/or associated with the research effort.**

Gerald Gabrielse, PI - Two months summer salary
Janet Ragusa, Administrative support (25%)
Paul Oxley, graduate student
Peter Yesley, graduate student
Hy Carrel, undergraduate student, summer salary
Michael Grobis, undergraduate student, summer salary
Inna Kozinsky, undergraduate student, summer salary
Caroline Troy, undergraduate student, summer salary
Halla Yang, undergraduate student, summer salary

5. **Publications: List peer-reviewed publications submitted and/or accepted during the grant period starting 1 August 1998.**

"Pretty Vacant",
G. Gabrielse,
New Scientist (Letter), *158(2138)*, 51 (1998).

"One-bit Memory Using One Electron: Parametric Oscillations in a Penning Trap",
C.H. Tseng, D. Enzer, G. Gabrielse and F.L. Walls
Phys. Rev. A *59*, 2094 (1999).

"Precision Mass Spectroscopy of the Antiproton and Proton Using Simultaneously Trapped Particles",
G. Gabrielse, A. Khabbaz, D.S. Hall, C. Heimann, H. Kalinowsky and W. Jhe
Phys. Rev. Lett. *82*, 3198 (1999).

"The Ingredients of Cold Antihydrogen: Simultaneous Confinement of Antiprotons and Positrons at 4 K",
G. Gabrielse, D.S. Hall, T. Roach, P. Yesley, A. Khabbaz, J. Estrada, C. Heimann, and H. Kalinowsky,
Phys. Lett. *B 455*, 311 (1999).

"Stochastic Phase-Switching of a Parametrically-Driven Electron in a Penning Trap",
L.J. Lapidus, D. Enzer and G. Gabrielse,
Phys. Rev. Lett. *83*, 899 (1999).

"Observing the Quantum Limit of an Electron Cyclotron: QND Measurements of Quantum Jumps Between Fock States"
S. Peil and G. Gabrielse
Phys. Rev. Lett. *83*, 1287 (1999).

"Field Ionization of Strongly Magnetized Rydberg Positronium: A New Physical Mechanism for Positron Accumulation"
J. Estrada, T. Roach, J.N. Tan, P. Yesley, and G. Gabrielse
Phys. Rev. Lett. *84*, 859 (2000).

"Comparing the Antiproton and Proton, and Opening the Way to Cold Antihydrogen",
G. Gabrielse,
In *Advances in Atomic, Molecular, and Optical Physics*, vol. 45, edited by B. Bederson and H. Walther, Academic Press, New York, pp. 1-39 (2001).

"One-Electron Quantum Cyclotron (and Implications for Cold Antihydrogen),
G. Gabrielse, S. Peil, B. Odom, and B. D'Urso,
In *Atomic Physics 17,* vol. 551, edited by E. Arimondo, P. DeNatale, M. Inguscio, American Institute of Physics, Melville, New York, pp. 108-120 (2001).

"First Positron Cooling of Antiprotons",
G. Gabrielse, J. Estrada, J.N. Tan, P. Yesley, N.S. Bowden, P. Oxley, T. Roach, C.H. Storry, M. Wessels, J. Tan, D. Grozonka, W. Oelert, G. Scheppers, T. Sefsick, W. Bruenlich, M. Carngelli, H. Fuhrmann, R. King, R. Ursin, H. Zmeskal, H. Kalinowsky, C. Wesdorp, J. Walz, K.S.E. Eikema, T. Haensch
Phys. Lett. B *507*, 1 (2001).

"Stability of a Combined Penning-Ioffe Trap"
T.M. Squires, P. Yesley and G. Gabrielse,
Phys. Rev. Lett. *86*, 5266 (2001.)

Thesis Supervised: " Quantum Jumps Between Fock States of an Ultracold Electron Cyclotron Oscillator"
Steven E. Peil
Harvard Ph.D. Thesis (May 11, 1999).

6. Interactions/Transitions:

a. Participation/presentations at meetings, conferences, seminars, etc.

1998

Aug. 7	16th International Conference on Atomic Physics (ICAP 16), Windsor, Ontario, Canada (Hot Topics Session (invited lecture)
Aug. 31	Trapped Charged Particles and Fundamental Physics, Monterey, CA (invited lecture)
Oct. 19	Cornell University (physics colloquium)
Nov. 7	CPT and Lorentz Symmetry Conference, Indiana University (invited lecture)

1999

Jan. 13	Institute for Medium Energy Physics of the Austrian Academy of Sciences, Vienna (physics colloquium)
Jan. 27	Queen's University, Kingston, Ontario, Canada (physics colloquium)
Jan. 28	Queen's University, Kingston, Ontario, Canada (invited lecture)
March 19	2nd North American FTICR Conference, San Diego, CA (invited lecture)
March 24	American Physical Society Centennial Meeting, Atlanta (invited lecture)
April 6	Michigan State University (physics colloquium)
May 24	Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference (invited lecture)
June 10	Lepton Moments, Internationales Wissenschaftsforum in Heidelberg (invited lecture)
June 11	Physikalisches Institut, Heidelberg (physics colloquium)
Aug. 2	1999 Workshop on Nonneutral Plasmas, Princeton University (invited lecture)
Sept. 13	4th International Conference on Physics at Storage Rings (STORI'99), Bloomington, IN (invited lecture)
Sept. 20	Carnegie Mellon University - University of Pittsburgh (joint physics colloquium)
Sept. 29	Trinity Christian College, Palos Heights, IL (Alumnus of the Year Lecture)
Nov. 4-6	Workshop on Fragmentation and Recombination in Novel 3- and 4-body Systems, ITAMP, CFA, Harvard University (invited lecture)

2000

Jan. 14	Argonne National Laboratory (physics colloquium)
Feb. 8	Boston University (physics colloquium)
Feb. 11	Tufts University (physics colloquium)
Feb. 17	Calvin College (physics colloquium)
Feb. 28	Harvard University (physics colloquium)
Mar. 23	American Physical Society March Meeting 2000, Minneapolis, MN (invited lecture)
Apr. 29	American Physical Society April Meeting 2000, Long Beach, CA (invited lecture)
June 5	17th International Conference on Atomic Physics (ICAP 2000), Florence, Italy (invited lecture)
July 5	International Conference on Quantum Communication, Measurement and Computing (QCM&C Y2K), Capri, Italy (invited lecture)
July 21	ITAMP Workshop on Quantum Electrodynamics, Harvard University (invited lecture)
Aug. 9	12th International Conference on Positron Annihilation (ICPA-12) (Munich) (invited lecture)
Aug. 24	Biennial Conference on Low Energy Antiproton Physics (LEAP 2000), Venice (invited lecture)
Sept. 13	Fall Teaching Orientation, Derek Bok Center for Teaching and Learning, Harvard University
Sept. 22	2nd Euroconference of Atomic Physics at Accelerators: Mass Spectroscopy

	(APAC 2000), Cargèse, Corsica (France) (invited lecture)
Oct. 30	38th Annual Briefing - New Horizons in Science, Council for the Advancement of Science Writing, Houston, TX (invited lecture)
Dec. 6	Fermilab (physics colloquium)
Dec. 15	Yale University (physics colloquium)

2001

Jan. 10	Schröedinger Lectures, Austrian Academy of Sciences, Vienna (invited lecture)
Jan. 10	"Junior Academy", discussion with high school students, Vienna
Jan. 11	University of Vienna (physics colloquium)
Jan. 15	Structure of Hadrons, International Workshop XXIX on Gross Properties of Nuclei and Nuclear Excitations (Hirschegg '01), Hirschegg, Kleinwalsertal, Austria (invited lecture)
Mar. 30	Columbia University (plasma physics colloquium)

b. Consultative and advisory functions to other laboratories and agencies, especially Air Force and other DoD laboratories. Provide factual information about the subject matter, institutions, locations, dates, and name(s) of principal individuals involved.

Consultant for Polychip, Inc., of Bethesda, Maryland, a small company seeking to produce portable gas sensors. Dr. Carl Ijames, principal chemist from Polychip will assist with our investigations. Dr. Ijames is an experienced FTICR instrument designer, super-user and spectroscopist. Polychip plans to bring their expertise in low cost manufacturing, notably in microelectro-mechanical systems (MEMS) and multichip electronic modules (MCM).

c. Transitions. Describe cases where knowledge resulting from your effort is used, or will be used, in a technology application. Transitions can be to entities in the DOD, other federal agencies, or industry. Briefly list the enabling research, the laboratory or company, and an individual in that organization who made use of your research.

NONE

7. **New discoveries, inventions, or patent disclosures. (If none, report None.)**

NONE

8. **Honors/Awards: List honors and awards received during the grant/contract period. List lifetime achievement honors such as Nobel prize, honorary doctorates, and society fellowships prior to this effort.**

Fellow of the American Physical Society, 1992
Harvard's Levenson Prize for Excellence in the Education of Undergraduates, 2000
Chair of the Harvard Physics Department, 2000 - 2003

REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-01-

0490

1. REPORT DATE *(DD-MM-YYYY)*
26-06-2001

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
01-04-1998 - 31-03-2001

4. TITLE AND SUBTITLE
Antiprotons, Antihydrogen and Mass Spectroscopy

5a. CONTRACT NUMBER

5b. GRANT NUMBER
F49620-98-1-0379

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER
2301/FS

5f. WORK UNIT NUMBER

6. AUTHOR(S)
Gerald Gabrielse

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Physics Department
Harvard University
17 Oxford Street
Cambridge, MA 02138

8. PERFORMING ORGANIZATION REPORT NUMBER 370 31710 133381 340642 0001 45187

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
President and Fellows of Harvard College
Office for Sponsored Research
Holyoke Center, 7th Floor
1350 Massachusetts Avenue
Cambridge, MA 02138

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S) 370 31710 133381 340642 0001 45187

12. DISTRIBUTION / AVAILABILITY STATEMENT

APPROVED FOR PUBLIC RELEASE

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH (AFOSR)
NOTICE OF TRANSMITTAL DTIC. THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLIC RELEASE LAW AFR 190-12. DISTRIBUTION IS UNLIMITED.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

A substantial storage ring facility is being constructed at CERN in order to allow us to produce and accurately study cold antihydrogen atoms for the first time. The initial focus is upon accumulating increased numbers of antiprotons and positrons, and then combining these antimatter particles to make antimatter for the first time. An eventual goal is using laser spectroscopy to accurately compare the properties of antihydrogen and hydrogen

15. SUBJECT TERMS
antiprotons, antihydrogen

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Gerald Gabrielse
				8	19b. TELEPHONE NUMBER *(include area code)* 617-495-4381 voice & fax

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18